Concept, Design and Performance of a Shape Variable Mashrabiya as a Shading and Daylighting System for Arid Climates

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ABSTRACT

The design of a solar protection system that can minimize solar gains while maximizing daylight and view to the outside is particularly challenging in arid climates, such as in the Middle-East, where sand, wind and corrosion impose specific constraints. We propose a system that provides a trade-off for three requirements: (i) maximize diffuse sunlight and view to the outside, (ii) efficiently block direct sunlight and (iii) transform a fraction of it into diffuse light for indoor daylighting. Compliance with this last requirement provides a solution for the common problem of insufficient daylighting even in the presence of abundant solar radiation, which often forces occupants to fully close their shading system and use electric lighting. In addition, our design potentially copes well with these extreme environmental conditions and preserves local architectural character (mashrabiya-inspired design). In this paper, we establish quantitative specifications for these three requirements, provide the working principle of our shading and daylighting system and its design, which consists of a shape variable mashrabiya (SVM). We calculate and analyze the annual daylighting performance of our SVM and benchmark it against the performance of Venetian blinds and diffuse sunlight alone. Finally, we provide the minimum reflectance required for the SVM to comply with our third requirement. We built a mock-up of our SVM to investigate the validity of our simulation model.

INTRODUCTION

The abundance of solar radiation in arid regions like in the Middle-East requires a very efficient shading system, in particular when aiming to provide visual comfort and prevent excessive solar gains. In addition, the combination of sand, wind and corrosion due to prevalent condensation creates harsh environmental constraints. On the one hand, the static vernacular solution named mashrabiya (perforated shield with oriental motifs) is well adapted to these constraints but fails to meet our contemporary needs for visual comfort due to insufficient daylighting and view to the outside. On the other hand, a kinetic shading system like Venetian blinds meets the requirements for efficient shading and for visual comfort (minimal glare, adequate daylighting and maximum view to the outside). However, to avoid excessive solar gains, such a shading system must be placed outside of the window, where it cannot withstand the harsh local environmental conditions. More sophisticated contemporary technologies embedded in the window, like electrochromic glass, are in principle unsuitable for these climates due to their propensity to absorb solar radiation resulting in excessive solar gains. Therefore, the challenge is to design a kinetic shading system that can cope with these harsh environmental conditions.

We propose a solution relying on a simple strategy to deal with abundant solar radiation that is applicable in these specific climatic conditions. With clear sky conditions prevailing throughout most of the year in these regions, strong direct sunlight on a window must be blocked without compromise. We believe that fine adjustments of the shading system with solar incidence angle are not strictly necessary, and not even desirable when striving to minimize solar gains. With this assumption, the shading system is closed in the presence of direct sunlight, and open when diffuse sunlight dominates. The sufficiency of such a binary function facilitates the design of a simple and robust kinetic shading system with the potential to cope with harsh climate conditions. Another important motivation for using a kinetic shading system with binary operation is the possibility to obtain a solar responsive system by exploiting a novel passive actuator. Applied as such, our approach would provide insufficient daylighting when blocking direct sunlight. This limitation, which is commonplace - independently of climatic conditions - in most shading systems, quite absurdly forces the occupants to use electric lighting despite abundant daylight availability. To tackle this, we devised a shading system that allows blocking direct sunlight while transforming a sufficient fraction of it into diffuse light for indoor daylighting. In addition to this key design-goal, we will devise a system that aims to preserve local architectural character.

In this paper, we provide the high-level requirements for this shading/daylighting system and explain its working principle. Then, we establish more detailed specifications and present the resulting design. We investigate the minimal reflectance required for the system to meet our daylighting goals and calculate annual daylighting performance. We close with a discussion of our results and benefits of this novel customized solar protection for arid climates.

SHADING AND DAYLIGHTING SYSTEM

High-level requirements

Our shading and daylighting system must comply with the following technological, functional, and architectural requirements: 1) ability to switch in a timely manner between an open and a closed configuration, in the absence and presence of direct sunlight, respectively; 2) maximal daylighting and view to the outside in the open configuration; 3) efficient shading and minimal solar gains in the closed configuration; 4) transformation of a sufficient fraction of the blocked incident direct sunlight into diffuse indoor daylight; 5) ability to withstand the harsh local climatic conditions; 6) potential for coupling our solar responsive system; 7) preservation of some local architectural character by using a mashrabiya-inspired design in both the open and close configurations. To reflect the above requirements, we will designate our system by "shape variable mashrabiya", abbreviated SVM.

Concept and working principle

Our SVM is made of three identical perforated opaque shields that can move relative to each other to switch between an open and a closed configuration (**Figure 1**). A shield consists of a bi-dimensional assembly of identical perforated motifs, each covering a square area with side-length ℓ.

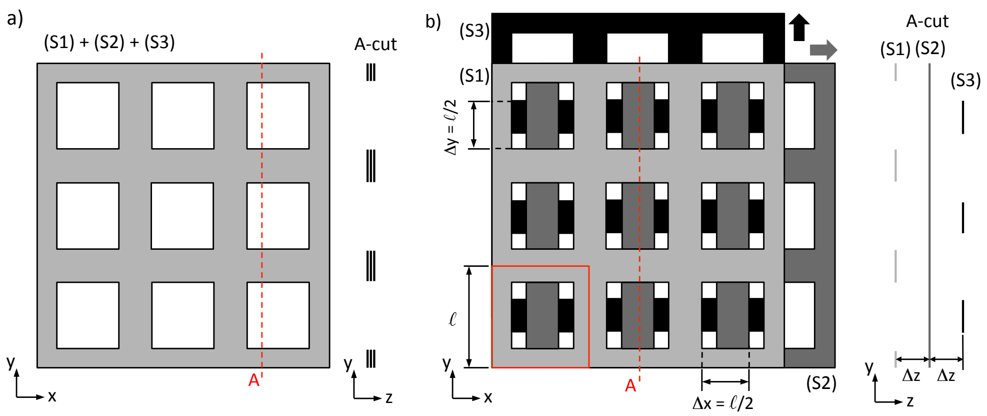

Figure 1 Concept and working principle of the SVM. (a) Open configuration. (b) Closed configuration.

The first shield is always motionless. In the open configuration (**Figure 1 (a)**), used when diffuse sunlight dominates, the shields are exactly superimposed and nearly in contact with each other. In the closed configuration (**Figure 1 (b)**), activated in the presence of direct sunlight, the second (S2) and third (S3) shields individually move along the vertical and lateral dimensions (x- and y-axis) by half of the motif length ($\ell/2$), respectively. Moreover, they both move in the z dimension to create a gap of length Δz between the shields, whose role is to allow multiple scattering reflections. As illustrated in **figure 2 (a)**), with an appropriate design, this results in the transformation of a significant fraction of direct sunlight into scattered light. Such a direct into diffuse light transformation (DDT) function must be optimized to obtain sufficient diffuse indoor daylighting.

To simultaneously move a shield along the lateral (x or y) and axial (z) dimensions, we devised a mechanism requiring few components and minimizing friction. It consists of a simple parallelepiped mechanical structure that allows switching between the two configurations by rotating the structure of an angle (γ), as depicted in **figure 2 (c)**. This structure allows simultaneously moving a whole assembly of mechanically interconnected shields from a single rotation point (P).

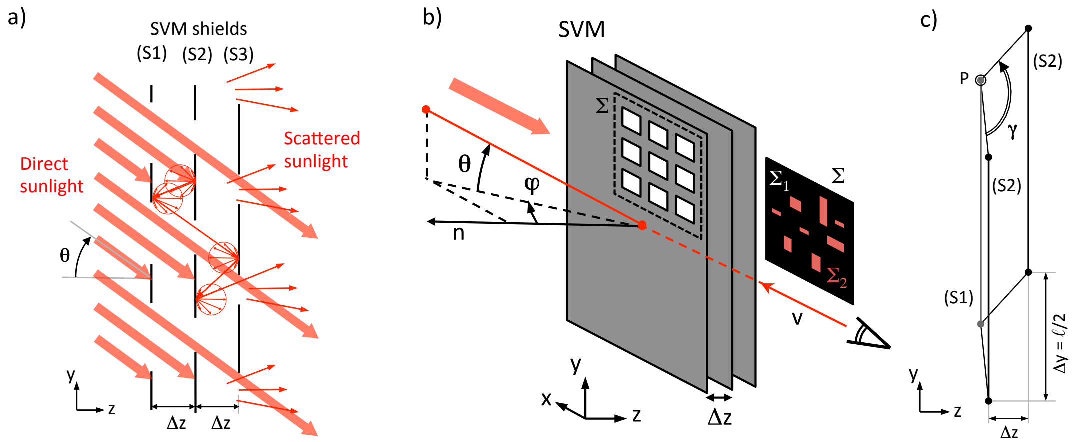

Figure 2 (a) Concept of the direct to diffuse light transformation (DDT) function. (b) Key geometrical parameters for defining the Shading Efficiency Factor (Γ), used in our specifications. (c) Mechanical concept for moving the SVM shields.

We plan to produce the required mechanical couple by means of a solar passive actuation and detection system based on a combination of custom optics and phase change material, which is currently being designed in our group. Such a solar responsive system, which is essentially restricted to binary actuation, lends itself well to moving our SVM. Since solar irradiation decreases with the cosine of incidence angle, solar gains are significantly reduced at elevation angles above 60°. Glare issues generally also become less critical in this angular range. Therefore, we designed our solar responsive system to switch from open to closed configuration at angles for $\theta < 60°$ and $|\varphi| < 60°$ (**Figure 2 (b)**).

The combination of such a simple solar responsive system (no detector, motor, electronics), whose description is outside of the scope of this paper, with this simple mechanical structure, is key to obtain a robust enough system potentially able to cope with the harsh local climatic conditions.

SPECIFICATIONS AND DESIGN OF OUR SHAPE VARIABLE MASHRABIYA (SVM)

Specifications

Shading. Specifications for shading depend on performance objectives, which are related to climate and to the usage of the space considered. Therefore, shading specifications are largely case-dependent. Here, we consider a public space (lobby, hall etc.) located in arid regions, for which glare and solar gains must be minimized. Such an objective can be formulated by means of a quantitative requirement on the maximum fraction of direct sunlight traversing the SVM structure. In the open configuration, since all three shields are superimposed, we simply need to specify the shading ratio (complement of the perforation ratio) of a shield of the SVM. Since, in the closed configuration, the shading ratio depends on the viewing direction (v), it is defined as: $\Sigma_1/\Sigma = (\Sigma_2 - \Sigma)/\Sigma$, where Σ_2 and Σ_1 are the illuminated and shaded surface portions of an area Σ (see **figure 2 (b)**). To establish a specification we need to introduce a more complex metric that accounts for this angular dependence of shading. We define the shading efficiency factor (Γ) as a percentage corresponding to the average shading ratio (μ) minus the standard deviation of this shading ratio (σ) for all viewing angles to be considered in the closed configuration, i.e. for $\theta < 60°$ and $|\varphi| < 60°$ (see above). Assuming a Gaussian distribution of these angular shading ratios, subtracting σ implies that the probability to have angular shading ratios lower than a specified Γ is of about 15%.

Based on these considerations and definitions, we establish, somewhat arbitrarily, the following two specifications with which our SVM must comply to best meet our high-level requirements #2 and #3:

A. In its open configuration, the shading ratio must be lower than 50%.
B. In its closed configuration, for $\theta < 60°$ and $|\varphi| < 60°$, one must have: $\Gamma > 90\%$

Direct into diffuse light transformation function (DDT). The DDT function efficiency (η) of the SVM is the ratio of direct sunlight transformed into diffuse light to the incoming direct sunlight in the closed configuration. Our specification for η is based on a benchmark and can be expressed as follows:

C. The DDT function of the SVM must provide daylighting at least equivalent to that provided by diffuse sunlight without a shading system (benchmark), throughout a whole typical meteorological year across the entire specific space considered.

Mechanical requirements. To reduce complexity and cost, no more than three shields must be used. To allow a simple and robust movement between the open and close configurations, as well as mechanical compliance with our passive actuation system, the mashrabiya shields S2 and S3 must move laterally (x-dimension) and vertically (y-dimension), respectively. Diagonal motions are not allowed.

Design and results

The final design of our SVM is the result of a trade-off between the mechanical and optical (A,B,C) specifications established above, while aiming for a mashrabiya-inspired design. Compliance with our mechanical specifications (three shields and orthogonal motions) is not easy to obtain given the conflicting specifications on shading for the open and the close configurations (max. shading ratio *versus* max. shading efficiency factor), in particular with the requirement of having a distance between the shield (Δz) and a mashrabiya-inspired design. Moreover, the shading efficiency factor (Γ), which must be maximized to meet the requirement for the closed configuration, decreases with the inter-shield distance Δz, while the DDT function efficiency increases with Δz, as explained later. What further complicates the design is that Γ does not vary as a function of Δz in a predictable manner because of the relatively complex geometry of the mashrabiya-inspired shield.

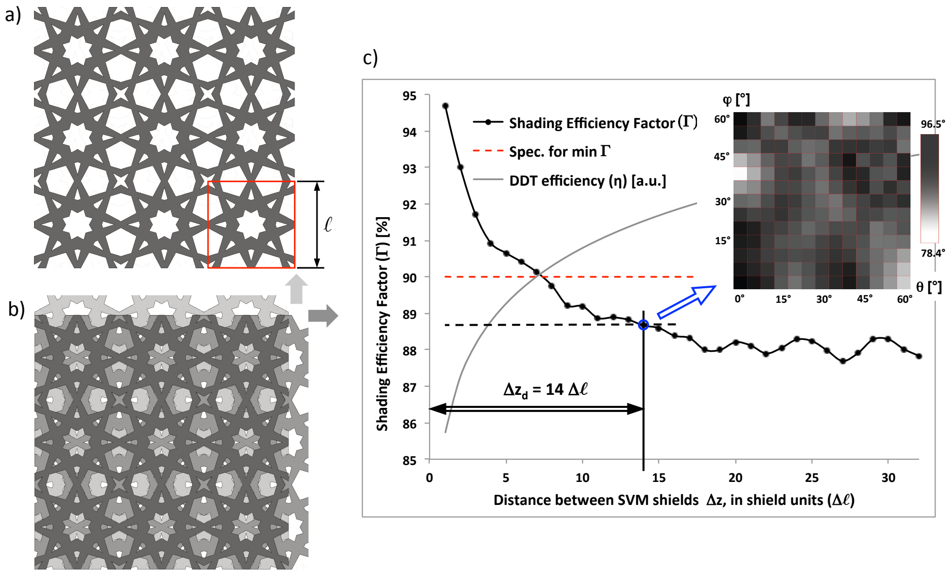

Figure 3 Resulting SVM design in (a) open configuration, and (b) closed configuration. (c) Plot of shading efficiency factor (Γ) and DDT function efficiency (η) against Δz, expressed in shield units $\Delta\ell = \ell/64$. Onset: Angular distribution of shading ratio at design trade-off distance $\Delta z_d = 14\Delta\ell$.

For our design, we used an iterative procedure with sequential calculations of Γ as a function of

Δz for different shield geometries till we found a viable trade-off. To get fast calculations of $\Gamma(\Delta z)$, we created a code in Grasshopper that calculates the shading ratio for all combinations of θ and φ angles varying in steps of 5° within the angular range ($\theta < 60°$ and $\varphi < 60°$), i.e., 169 combinations. The best trade-off we obtained led to the shield geometry shown in **figure 3 (a)**. The corresponding closed configuration is shown in **figure 3 (b)**. With this trade-off, we obtained a shading ratio of 54.1% and a shading efficiency factor of 88.7%, both values out of specifications (<50% and >90%, respectively). **Figure 3 (c)** shows the room for trade-off in the closed configuration between the variables Γ and η with conflicting trends.

Figure 3 (c) shows the plot of the DDT function efficiency $\eta(\Delta z)$, which corresponds to a fit across values calculated further in this paper. As shown in this figure, η increases with Δz with a horizontal asymptotic behavior while Γ, calculated with our Grasshopper code, decreases with Δz in a similar way. The distance Δz is expressed in a dimensionless unit corresponding to a fraction of the shield length motif (ℓ), which is $\Delta\ell = \ell/64$ (arbitrary choice). We used this unit because Δz ultimately only depends on the motif length, which is *a priori* unknown and remains a free design parameter (see below). In principle, to meet our specs for Γ, Δz must be smaller than $8\Delta\ell$ (**figure 3(c)**). For our trade-off, we preferred to have higher η at the expense of an only marginally lower Γ (88.7%) corresponding to $\Delta z_d = 14\Delta\ell$, which is the inter-shield distance used in our design. The **onset of figure 3 (c)** provides quantitative insights into the shading ratio versus the angle of view (θ and φ) at Δz_d.

Our design procedure has provided the shape of the shield and the relative size of the SVM structure ($\Delta z_d/\ell$). The absolute size of the SVM, i.e. $\Delta\ell$, and in turn Δz_d, was determined by a subjective appreciation of the most suitable scale of our SVM for best acceptability in its open configuration, with respect to interference with view to the outside and visual aspect in a room. To this aim, we carried out a brief survey based on a real-scale mock-up and computer rendering simulations. This resulted in a general consensus that a suitable motif size (ℓ) is of the order of ℓ = 16 cm. This value yields an amplitude of displacement $\Delta x = \Delta y = \ell/2 = 8$ cm and a distance $\Delta z_d = 14\,\Delta\ell = 14\,\ell/64 = 3.5$ cm.

DAYLIGHTING PERFORMANCE

To gain quantitative insights into indoor daylighting with our SVM, we need to evaluate the annual daylighting performance in a relevant case-study. Another specific goal is to determine whether our SVM - in its closed configuration - allows comparable or superior illumination than that provided by diffuse sunlight. First, we need to optimize the DDT function of our SVM.

Optimization of DDT function

The DDT function efficiency (η) of the SVM, i.e., the ratio of direct sunlight transformed into diffuse light to the incoming direct sunlight, mainly depends on three parameters: the angular intensity scattering distribution of the shield material - characterized by the "specularity" parameter (S) in RADIANCE, the distance between the shields (Δz), and the reflectance of the shield material (R).

To investigate the first two parameters (S and Δz), we opted for a brief sensitivity analysis by means of "point-in-time" simulations with the software DIVA-for-Rhino, which exploits RADIANCE algorithms. Light scattered by the SVM was measured as a function of S and Δz at a location free from any direct sunlight contribution (ceiling). First, the parameter S was varied in five equal steps of 0.2 between a Lambertian and a much more specular intensity scattering distribution (S = 0.1 and S = 0.9 in RADIANCE, respectively). Quite surprisingly, the simulations revealed that η is nearly independent of specularity. The parameter Δz was then increased in five even steps between $\Delta z = \ell/10$ to $\Delta z = \ell/2 = 8$ cm. The simulation results revealed that η increases with Δz with a horizontal asymptotic trend. As shown earlier, this is the specification on Γ that sets a limit on η leading to the optimal trade-off distance of $\Delta z_d = 3.5$ cm. Due to lack of space, we do not provide all the details of this sensitivity analysis.

Given that η obviously increases with reflectance, such an analysis is not required for this parameter. However, since the maximum reflectance value is practically limited by the availability of suitable materials and by ageing - especially when exposed to outdoor conditions - it is essential to determine the minimum value for R that allows for compliance with our specifications on η (see above). One option to find the minimal R would be to carry out a sensitivity analysis by means of annual daylighting simulations. However, since these simulations are very time consuming (around eight days) with the available computer resources, and are thus impractical for such a sensitivity analysis, we opted for getting a rough estimate of the minimum R required using the method described below.

Determination of minimum reflectance: method and results. Our goal is to find out what is the minimal reflectance of our SVM that provides, in closed configuration, an illumination just superior to that provided by diffuse sunlight without any solar protection. Since our SVM is meant to be used in arid climates, we chose to carry out our investigation for Abu Dhabi (latitude 24.47°). Our method relies on point-in-time simulations with average values representative of the typical climate that prevails at this location. Calculation of the average diffuse sunlight - which corresponds to our benchmark - is based on the yearly average of all data for diffuse horizontal irradiance (between sunrise and sunset) provided in typical meteorological year (TMY) files. For Abu Dhabi this value was found to be equal to 130 W/m^2. In a similar fashion, calculation of direct average sunlight illumination was based on the yearly average of all TMY data for direct horizontal irradiance with elevation and azimuth angles falling in the angular range corresponding to the closed SVM (same range as used for the calculation of Γ). We found a value of 479 W/m^2, which is used in our simulations at the mean angle of the range considered, i.e., at an elevation angle of 30°. Our calculations, which are performed with the Perez sky model in DIVA-for-Rhino, account for both the direct and the diffuse sunlight contributions.

Our simulation model consists of a rectangular volume with a square side covered by our SVM. We use one millimeter thick shields made of ten by ten motifs, corresponding to a size of 160 by 160 cm^2. To avoid direct sunlight, we calculated the illuminance as a function of the distance for the SVM (I(z)) along an axis centered on the ceiling-wall of our space, which is delimited by fully absorbing walls. The material of the shields had Lambertian scattering properties (S = 0, in RADIANCE).

Results and analysis. The results of our sensitivity analysis for the reflectance, obtained with point-in-time simulations using the method described above, are shown in **figure 4 (a)**. The illuminance I(z) calculated on the ceiling measurement axis is plotted for a few reflectance values (R=0.5, R=0.7, R=0.8, R=0.9) against our benchmark corresponding to yearly average diffuse sunlight in Abu Dhabi. These plots correspond to exponential fits through average illuminance values calculated at forty evenly spaced sensors along the ceiling measurement axis, which is approximately 210 cm long.

These results suggest that a reflectance larger than R = 0.7 gives an indoor illuminance slightly larger than that obtained with average diffuse sunlight conditions. Compliance with this key specification for R is demanding but still practically attainable with widespread materials.

Our relatively simple method can only provide rough figures for the benchmark and reflectance plots. Indeed, our point-in-time simulations are based on average quantities for diffuse and direct sunlight, and on a single average incidence angle for the latter. Moreover, we need to account for both spatial and temporal distribution of illuminance on the whole measurement plane. Annual daylighting simulations can provide more comprehensive and reliable figures, and improve our estimate of R.

Annual daylighting performance

Method. For the annual daylighting simulations, we considered a standard room with a West-facing glass wall. We analyzed and compared the annual daylighting performance obtained for three cases: a double pane glass wall without shading system, standard Venetian blinds and our SVM. The Venetian blinds are mounted on a double pane glass wall with 65% transmission, whereas the SVM in mounted on a double pane glass with low-E coating yielding 80% transmission. The room has a depth, width and height of 5 m, 3.52 m and 3.04 m, respectively. The sensor plane lies at a height of 85 cm with a clearance of 60 cm from the walls. This yields a sensor plane of 2.32 m x 3.8 m, which was divided into a grid of 160 sensors, each measuring 23.2 x 23.75 cm. The floor, walls, and ceiling were modeled as Lambertian scattering surfaces with a reflectance of 0.3, 0.65 and 0.8, respectively. The SVM shields have a reflectance R = 0.8 and Lambertian scattering properties. The configuration of the SVM, as well as the orientation of the Venetian blinds, are determined by the angle of incidence of direct sunlight according to the acceptance angle specified for our solar responsive actuation system (see above).

For our calculations with the Venetian blinds, we used the same simplified model as implemented in the DAYSIM interface, in which three tilt angles (β) of the blinds are determined by the solar incidence angle (θ) depending on specific angular thresholds. We used $\beta = 0°$ for $\theta < 15°$, $\beta = 30°$ for $15° < \theta < 30°$, and $\beta = 60°$ for $30° < \theta < 90°$, where β is taken relative to the window surface. This model uses standardized occupants behaviors. In the so-called "passive" behavior used here, the occupant leaves the blinds in their horizontal position ($\beta = 90°$) for long times dominated by diffuse sunlight (e.g. in the morning for a West-oriented façade). An algorithm, which we wrote in Python, was used to determine the moments throughout a typical year (8760 hours) corresponding to the specific angles that determine the sequence of actuation for either shading systems considered (SVM and blinds). The illuminances corresponding to this sequence, which are calculated by DIVA-for-Rhino with the Perez sky model, are used for the calculation of temporal maps.

Results and analysis. Temporal maps are used to present the results of our annual daylighting performance simulations obtained for a double pane glass wall without shading system, with standard Venetian blinds, and with our SVM made of shields with reflectance R = 0.8 (**Figure 4 (b)**). The triangular color scale allows showing the Acceptable Illuminance Extent (AIE), introduced by [Kleindeinst *et* al. 2012] to provide a visual representation of the fraction of our sensor grid that is above, below or within the illuminance range considered. Our range, which we call useful daylight illuminance autonomous (UDI-a), following Marjalevic's definition, is defined by bottom and top boundaries of 500 and 3000 lux (sharp cut-offs), respectively [Mardjalevic, 2009].

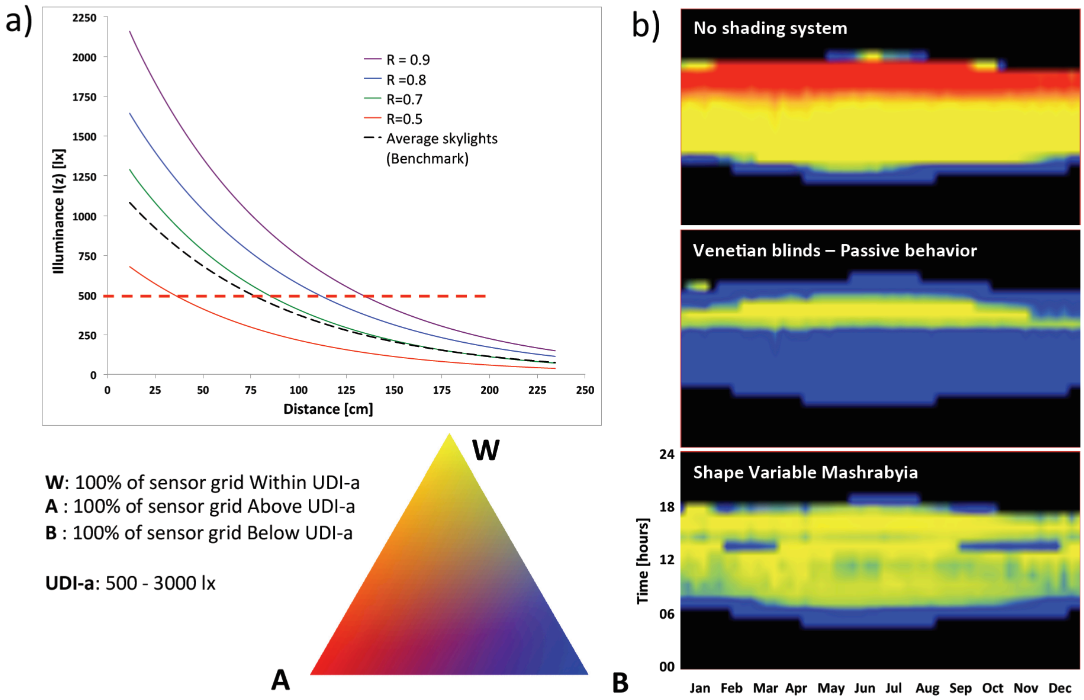

Figure 4 Annual daylighting performance for a West-facing room. (a) Average-based point-in-time simulations for closed SVM. (b) Temporal maps for three cases, including closed SVM with shield reflectance R = 0.8. Triangular color scale allows showing spatial intensity distributions.

Without a shading system, illuminance exceeds our high boundary of 3000 lux nearly all afternoon-times (solar noon to sunset) for most of space, as expected for a West-orientation. During morning-times (sunrise to solar noon), illuminance falls within the UDI-a boundaries (500 – 3000 lx) for the whole space except at dawn-times. With Venetian blinds, assuming passive occupants behavior, illuminance falls within the UDI-a boundaries only in the middle of afternoon-times and below the low-

UDI-a boundary of 500 lux for the rest of time. At sunset-times, when Venetian blinds must block abundant direct sunlight, which quite absurdly yields insufficient daylighting, the DDT function of our SVM manages to ensure adequate daylighting. This key design-objective for our SVM was translated into a specification for the DDT function efficiency that we are now in a position to assess in more detail than with our simple investigation based on average point-in-time simulations. Comparing the illumination obtained with our closed SVM exposed to direct sunlight (afternoon-times) *versus* illumination produced by diffuse sunlight only, i.e. without shading system during morning-times, reveals that adequate illumination is reached in both cases. However, when considering the whole temporal map with spatial information, illumination with diffuse sunlight proves to be slightly superior than with our closed SVM made of shields with reflectance of 0.8 under direct sunlight. In principle, this reveals that the efficiency of our DDT function (η) is slightly below our specification and that the above mentioned simple investigation was too optimistic.

However, a thorough investigation (outside of the scope of this paper) revealed that our simulation provides reliable trends for spatial illuminance distributions but underestimates the amount of diffuse light scattered by the SVM, i.e. η. Such a bias is caused by an insufficient number of simulation iterations imposed by the lack of available computational power. This investigation was based on the comparison of point-in-time simulations with corresponding measurements on a mock-up of our SVM. Further investigation is needed to estimate more accurately the magnitude of this bias and reliably account for it in our results. This mock-up was also used to get insights into aesthetics of our SVM.

DISCUSSION AND CONCLUSION

We have presented the design of a shading and daylighting system customized for arid climates focused on also preserving a Middle Eastern architectural character. Such a kinetic system design, which we named “shape variable mashrabiya” (SVM), strives to maximize visual comfort and minimize solar gains, while potentially coping with the harsh local environmental conditions. Our SVM enables to switch between an open and a closed configuration depending on direct solar irradiation. The latter configuration, which consists of a three-dimensional structure, blocks most incident sunlight while transforming a fraction of it into diffuse light used for indoor daylighting (DDT function).

Our results of annual daylighting performance simulations show that, thanks to its DDT function, our SVM provides adequate (within the UDI-a boundaries) and well-balanced (most of the time across the whole space) illumination, even in the presence of direct sunlight. In particular, in contrast to typical Venetian blinds, it provides sufficient daylighting under direct sunlight at low elevation angles. Considering that our simulations provide pessimistic figures for the DDT function efficiency (see discussion in last section), our results reveal that our closed SVM with shield reflectance of the order of 0.8 should provide comparable illumination than that obtained with diffuse sunlight. In addition to increasing daylight autonomy, i.e., allowing for energy savings, we believe that our SVM design bears some architectural value and aesthetic appeal that may favor its acceptability.

Future or ongoing work covers, among other things, the design and integration of the solar responsive system, the integration of an array of SVM into a facade, investigation of energy performance and field-tests to validate the robustness of our design in arid climates.

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